An Interoperability Concept for Detect and Avoid and Collision Avoidance Systems: Results from a Human-in-the-Loop Simulation

Conrad Rorie

The integration of Unmanned Aircraft Systems (UAS) into the National Airspace System (NAS) poses a variety of technical challenges to UAS developers and aviation regulators. In response to growing demand for access to civil airspace in the United States, the Federal Aviation Administration (FAA) has produced a roadmap identifying key areas requiring further research and development. One such technical challenge is the development of a "detect and avoid" system (DAA) capable of providing a means of compliance with the "see and avoid" requirement in manned aviation. The purpose of the DAA system is to support the pilot, situated at a ground control station (GCS), in maintaining "DAA well clear" of nearby aircraft through the use of GCS displays and alerts. In addition to its primary function of aiding the pilot in maintaining well clear, the DAA system must also safely interoperate with existing NAS systems and operations, such as the airspace management procedures of air traffic controllers (ATC) and Collision Avoidance (CA) systems currently in use by manned aircraft, namely the Traffic alert and Collision Avoidance System (TCAS) II. It is anticipated that many UAS architectures will integrate both a DAA system and a TCAS II. It is therefore necessary to explicitly study the integration of DAA and TCAS II alerting structures and maneuver guidance formats to ensure that pilots understand the appropriate type and urgency of their response to the various alerts. This paper presents a concept of interoperability for the two systems. The concept was developed with the goal of avoiding any negative impact on the performance level of TCAS II while retaining a DAA system that still effectively enables pilots to maintain DAA well clear.

The interoperability concept described in the paper focuses primarily on facilitating the transition from a late-stage DAA encounter (where a loss of well clear is imminent) to a TCAS II Corrective Resolution Advisory (RA), which requires pilot compliance within five seconds of its issuance. The interoperability concept was presented to 10 participants (6 active UAS pilots and 4 active commercial pilots) in a medium-fidelity, human-in-the-loop simulation designed to stress different aspects of the DAA and TCAS II systems. Pilots' ability to maintain separation, their rate of compliance and response times using the interoperability concept are reported. Results indicated that pilots exhibited comprehension of, and appropriate prioritization within, the DAA-TCAS II

combined alert structure. Pilots demonstrated a high rate of compliance with TCAS II RAs and were also seen to respond to corrective RAs within the five second requirement established for manned aircraft. The DAA system presented under test was also shown to be effective in supporting pilots' ability to maintain DAA well clear in the overwhelming majority of cases in which pilots had sufficient time to respond.

Unmanned Aircraft Systems (UAS) Integration in the National Airspace System (NAS) Project

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Human Systems Integration

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Background

- Detect and Avoid (DAA) is a means of compliance with Title 14 Code of Federal Regulations (14CFR) Part 91, which dictate:
  - Pilot is ultimately responsible for practicing vigilance to avoid collision hazards
    - This authority includes the right to deviate while flying Instrument Flight Rules (IFR)
  - Pilot applies their own judgement as to whether there is a violation of well clear
- When quantifying well clear for Unmanned Aircraft Systems (UAS) operations (i.e., “DAA Well Clear”), existing systems had to be taken into account:
  - Air traffic management – undesirable to disrupt current flows/procedures
  - Collision avoidance systems – need to avoid triggering excessive collision avoidance maneuvers on UAS and manned aircraft

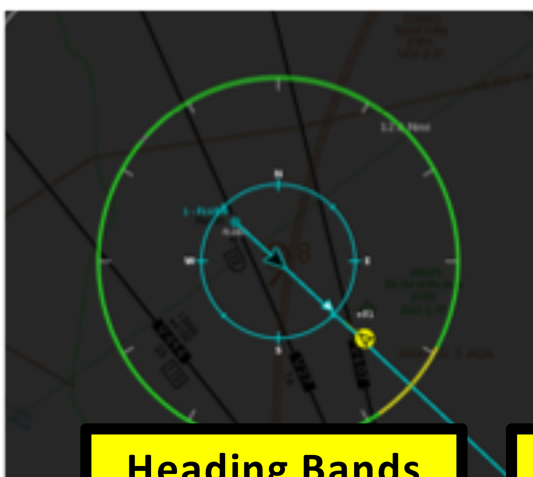
Background

- Multiple classes of UAS are defined by the Phase 1 Minimum Operational Performance Standards (MOPS) for UAS DAA systems (developed by RTCA SC-228)
  - Class 1 = UAS equipped with active airborne surveillance (e.g., Mode S), ADS-B In, and an air-to-air RADAR (ATAR)
    - Enables DAA operations – alerts/guidance to maintain & regain DAA well clear
    - *Minimum* equipage
  - Class 2 = Traffic Alert and Collision Avoidance System (TCAS II) (+ DAA)
    - Enables Collision Avoidance (CA) operations – alerts/guidance to avoid collision
    - CA maneuvers are coordinated with other TCAS II-equipped aircraft
    - *Optional* equipage

❖ The integration of TCAS II and DAA in a Class 2 system requires substantial investigation since they rely on different assumptions and capabilities

Background

- DAA System
  - Protects against **all intruder types** (cooperative & non-cooperative)
  - Issues caution and warning-level alerts and guidance in order to remain/regain DAA well clear
    - Issues a caution-level ‘preventive’ alert against traffic that is safely separated but close enough to warrant an alert (i.e., do not climb/descend into the traffic)
  - **Suggestive** guidance issued to help pilots determine how to remain/regain DAA well clear
    - Displayed as ‘banding’ that highlights headings/altitudes to avoid in order to maintain DAA well clear
    - Regain DAA well clear guidance shows ‘wedge’ of headings/altitudes to target when loss of well clear is unavoidable



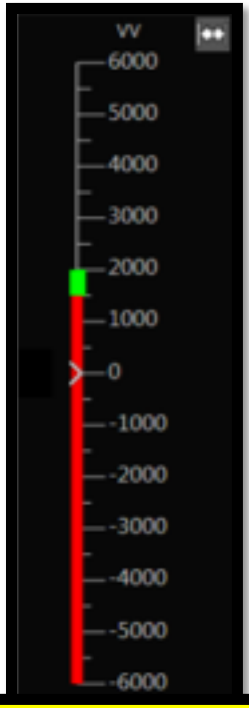
Heading Bands

Altitude Bands

Regain Well Clear Guidance

Background

- TCAS II System
  - Protects against **cooperative intruders only** (i.e., equipped with Mode C/S)
  - Issues caution-level alerts (*Traffic Advisories,* TAs) and warning-level alerts (*Resolution Advisories,* RAs)
    - TAs aid the pilot in acquiring the traffic visually in anticipation of an RA
    - RAs can be both Preventive (i.e., “do not climb/descend”) and Corrective (“climb/descend”)
  - **Directive** vertical rate guidance accompanies all RAs - expectation that pilot will comply *within 5s*



Vertical Rate Guidance

Background

- A DAA-TCAS Interoperability Workshop was held at NASA Ames Research Center to discuss issues and potential solutions regarding integration
  - Members of SC-228 and the TCAS Program Office were in attendance

- Primary issues confronting a Class 2 system are:
  - Detection of intruders
    - In order to generate Resolution Advisories the intruder must have a transponder with altitude reports (e.g., Mode C or S)
    - Possible for RAs to be in the direction of non-cooperative traffic
  - Alerting structures & maneuver guidance
    - Both the TCAS and DAA systems include different caution and warning-level alerting that could be perceived as contradictory
    - DAA maneuver guidance is not coordinated with TCAS maneuver guidance – particularly important with guidance to **regain** DAA well clear
    - Could lead to confusion and/or frustration

Background

- DAA-TCAS Interoperability Concept:
  - General TCAS II modifications:
    - Corrective RAs will always be presented to pilots, and the expectation will always be for pilots to comply with the guidance (ideally within 5sec)
    - Preventive RAs (i.e., “Do not climb/descend”) presented as Preventive DAA alerts
    - Traffic Advisories (TAs) will be suppressed, and replaced by DAA alerts and guidance
  - General DAA modifications:
    - Maintain use of 2 different warning-level alerts (one for DAA and one for TCAS II)
    - Vertical guidance to regain DAA well clear is suppressed for cooperative intruders
  - During an *active* TCAS II Corrective RA, the DAA system shall:
    - Remove the RA intruder from calculation of horizontal DAA guidance
    - Fully suppress vertical DAA guidance
    - Issue guidance to regain DAA well clear if a secondary, non-cooperative intruder triggers a DAA warning alert

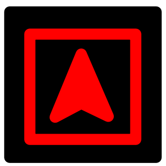
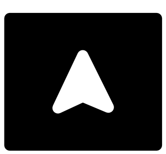
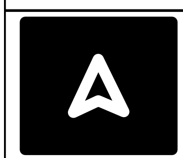
❖ Characterize pilot & system performance with interoperability concept developed at workshop

Experimental Design

- Participants:
  - 6 active duty UAS pilots
    - Average Age: 36
    - Manned Flying Experience Total Hours: 1600
    - Unmanned Flying Experience Total Hours: 1400
  - 4 commercial pilots
    - Average Age: 30
    - Manned Flying Experience Total Hours: 9000

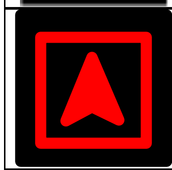
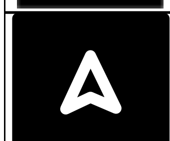
- Simulation Hardware/Software:
  - Vigilant Spirit Control Station (VSCS) served as ground control station (GCS)
    - Displayed DAA and TCAS alerting and guidance
    - Vehicle controls
  - TCAS II v 7.0 logic (with 7.1 aural alerts)
  - Java Architecture for DAA and Extensibility (JADEM; developed at NASA Ames) served as experimental DAA System
    - Perfect surveillance data (no uncertainty models applied)

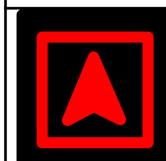
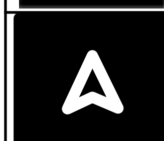
Experimental Design

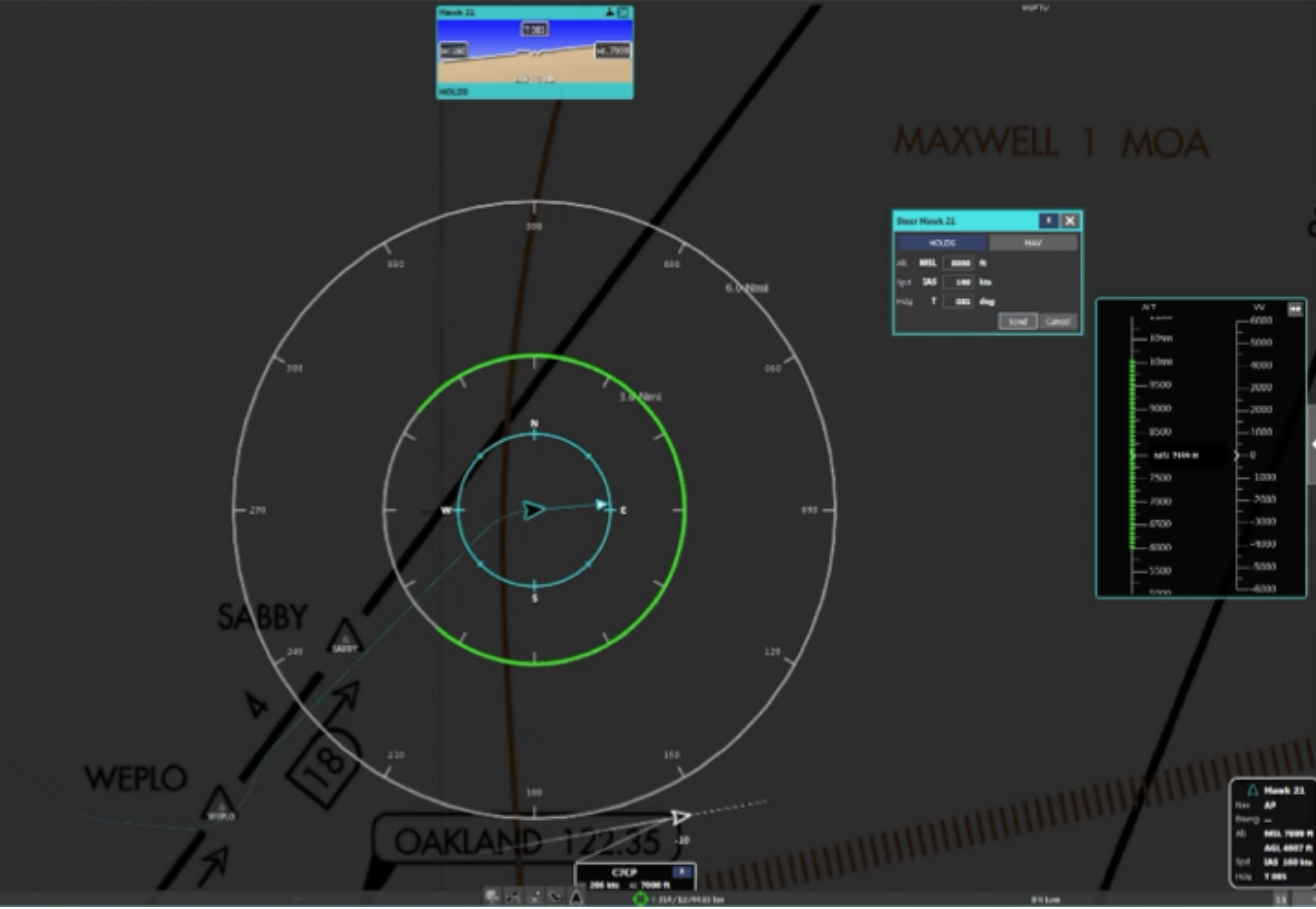
Symbol	Name	Pilot Action	Buffered Well Clear Criteria	Time to Loss of Well Clear	Aural Alert Verbiage
	TCAS RA	• **Immediate action required** • Comply with RA sense and vertical rate • Notify ATC as soon as practicable after taking action	*DMOD = 0.55 nmi *ZTHR = 600 ft *modTau = 25 sec	0 sec (+/- 5 sec) (TCPA approximate: 25 sec)	"Climb/Descend"
	Self Separation Warning Alert	• ***Immediate action required*** • Notify ATC as soon as practicable after taking action	DMOD = 0.75 nmi HMD = 0.75 nmi ZTHR = 450 ft modTau = 35 sec	25 sec (TCPA approximate: 60 sec)	"Traffic, Maneuver Now"
	Corrective Self Separation Alert	• On current course, ***corrective action required*** • Coordinate with ATC to determine an appropriate maneuver	DMOD = 0.75 nmi HMD = 0.75 nmi ZTHR = 450 ft modTau = 35 sec	55 sec (TCPA approximate: 90 sec)	"Traffic, Avoid"
	Preventive Self Separation Alert	• On current course, corrective action ***should not be required*** • Monitor for intruder course changes • Talk with ATC if desired	DMOD = 0.75 nmi HMD = 1.0 nmi ZTHR = 700 ft modTau = 35 sec	55 sec (TCPA approximate: 90 sec)	"Traffic, Monitor"
	Self Separation Proximate Alert	• Monitor target for potential increase in threat level	DMOD = 0.75 nmi HMD = 1.5 nmi ZTHR = 1200 ft modTau = 35s	85 sec (TCPA approximate: 120 sec)	N/A
	None (Target)	• No action expected	Within surveillance field of regard	X	N/A

* These values show the Protection Volume (**not well clear volume**) at MSL 5000-10000ft (TCAS Sensitivity Level 5)

Experimental Design

Cooperative Aircraft		
Symbol	Name	Aural Alert Verbiage
	TCAS RA	"Climb/Descend"
	DAA Warning Alert	"Traffic, Maneuver Now"
	Corrective DAA Alert	"Traffic, Avoid"
	Preventive DAA & RA	"Traffic, Monitor"
	None (Target)	N/A

Non-Cooperative Aircraft		
Symbol	Name	Aural Alert Verbiage
	DAA Warning Alert	"Traffic, Maneuver Now"
	Corrective DAA Alert	"Traffic, Avoid"
	Preventive DAA & RA	"Traffic, Monitor"
	None (Target)	N/A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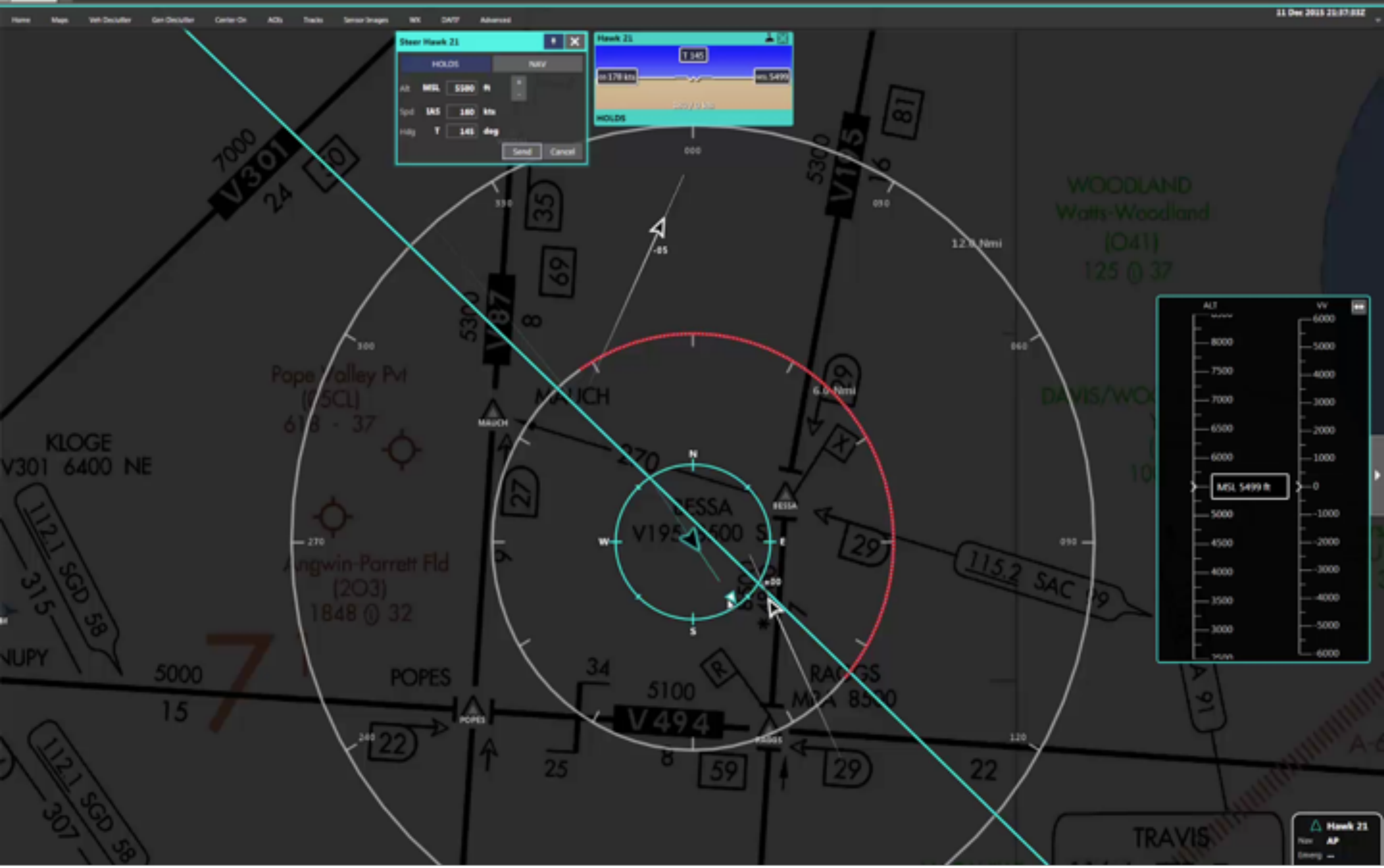
Experimental Design

- Test set up:
  - Pilots flew a simulated MQ-9 on straight flight path
    - No secondary tasks or background traffic
    - Researcher served as ATC confederate
  - 4 60-minute experimental trials
    - 16 encounters per trial (~1 encounter every 4min)
  - Encounters were designed to conform to 4 specific use cases designed to stress specific aspects of the interoperability concept
  - Encounters within each use case were flown in 2 different ways:
    - <u>Non-Blunder</u> – nominal case; the intruder was scripted to result in use case from the get-go, i.e., pilot had full alert timeline to resolve *before* use case would occur
    - <u>Blunder</u> – intruder was scripted to make a last-second maneuver *into* the UAS to force the purpose of the use case



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AP

Use Cases

Multi-Threat	Use Case #	Intruder Type(s)	Purpose
No	1	Non-cooperative	Generate guidance to regain DWC
	2	Cooperative	Generate TCAS II RA
Yes	3	Cooperative & Non-cooperative	Generate secondary DAA warning alert with non-cooperative intruder following compliance with TCAS II RA
	4	Cooperative & Non-cooperative	Generate secondary corrective DAA alert with non-cooperative intruder following compliance with TCAS II RA

Research Questions

- How often did an intruder lose DAA well clear and/or trigger a TCAS RA?
  - As function of blunder vs. non-blunder
  - As function of primary vs. secondary intruder
- When a loss of DAA well clear or an RA occurred:
  - Did pilots comply with the guidance to regain well clear and/or TCAS II RA guidance?
  - Reasons for non-compliance
- What were pilot response times?
  - As function of blunder vs. non-blunder
  - Did response to TCAS RA approach 5sec requirement?

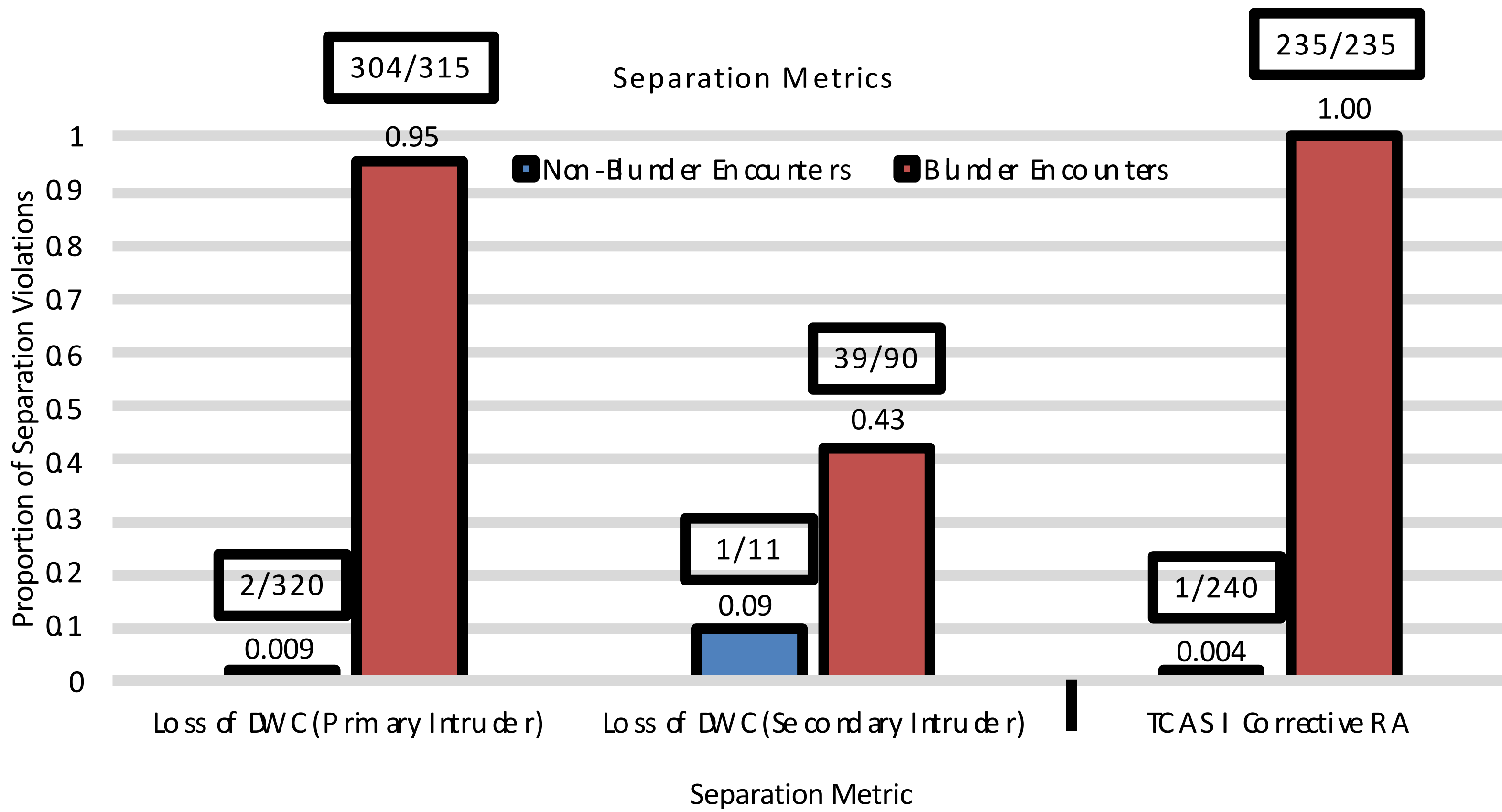
Metrics

- Separation
  - Loss of DAA Well Clear (LoDWC) Proportion = instances of DAA well clear / total DAA Corrective or Warning alerts
  - TCAS II Corrective RA Proportion = instances of Corrective RAs / total encounters designed to generate Corrective RA
- Compliance
  - Regain DAA Well Clear Guidance Compliance Proportion = instances of compliance / total number of issuances
  - TCAS II RA Guidance Compliance Proportion = instances of compliance / total number of Corrective Ras
- Response Time
  - Initial Response Time = time to start input into GCS following alert
  - Initial Edit Time = time to complete input into GCS
  - Aircraft Response Time = initial response + initial edit time

RESULTS

Results

- The rate of separation violations was overwhelmingly determined by the encounter type (non-blunder vs. blunder)
  - Almost no separation violations occurred against non-blundering traffic
    - 3 total losses of DAA well clear; 1 TCAS II Corrective RA
  - As expected, almost all primary blunder encounters resulted in a loss of DWC or an RA



Results

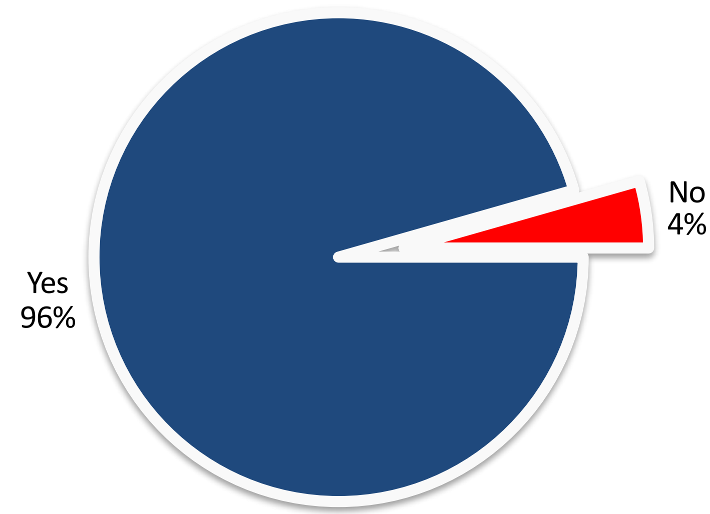
- Losses of DWC in Non-Blunder Encounters
  - 1 case of pilot returning to course too soon after having successfully resolved it initially (occurred in Use Case 2)
  - 2 cases of pilots having difficulty interpreting the DAA alerting and guidance (1 each in Use Cases 3 & 4)

- Secondary conflict in Blunder Encounters
  - 38 of 39 instances of loss of DWC with secondary intruder occurred in Use Case 3 (secondary threat was a warning alert)
    - Pilots nearly completely avoided losses of DWC with secondary threat when intruder was a corrective (Use Case 4)
  - Pilots frequently avoided a conflict with the secondary aircraft entirely by making horizontal maneuver in addition to complying with TCAS II RA

Results

- Compliance
  - Nearly perfect compliance with both regain DAA well clear & RA guidance
    - 97% (296/304) of the time pilots complied with guidance to regain DAA well clear
    - 96% (225/235) of the time pilots complied with TCAS II RA guidance

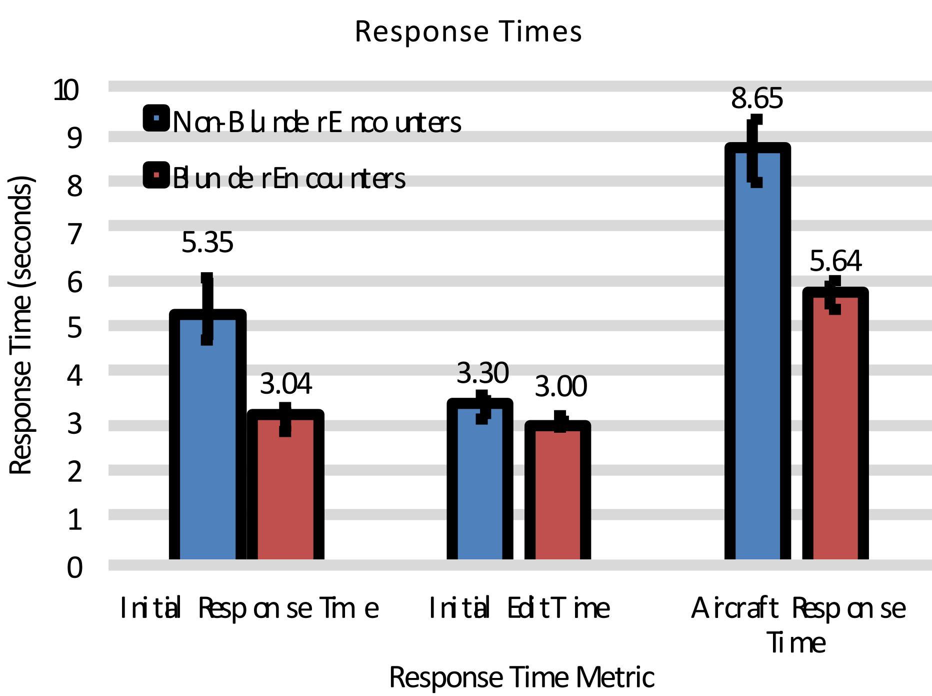
Overall Compliance w/ Guidance

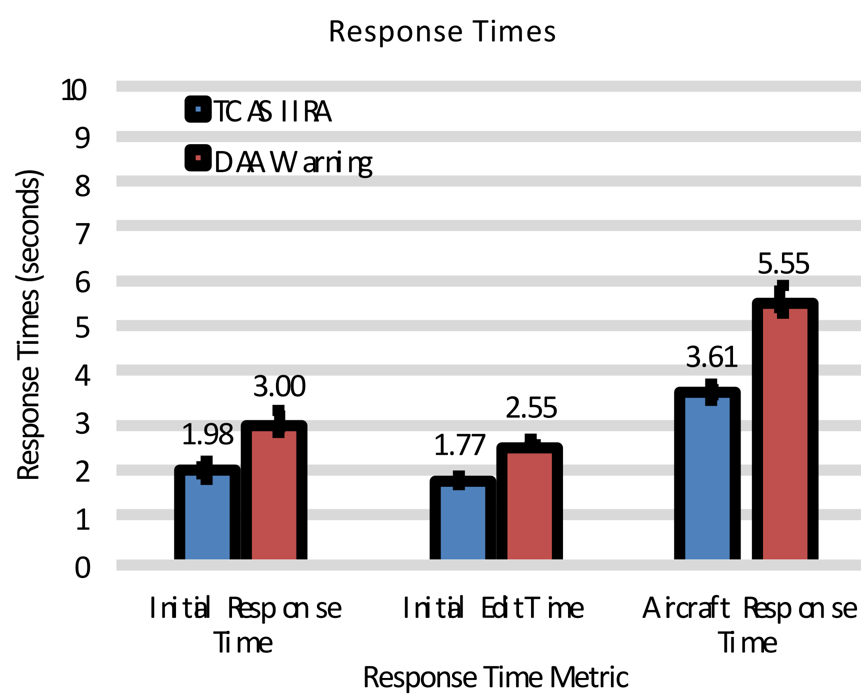


- Non-compliance
  - Regain DAA well clear guidance - most common was pilots had already initiated a maneuver in a different direction and felt a second maneuver was unnecessary
  - TCAS II RA guidance – most common reason was pilot (apparently) being aware of secondary traffic in direction of the RA (all Use Case 3)
    - 6 instances where pilot maneuvered in the opposite sense as RA
    - 3 instances where pilots only made a horizontal maneuver

Results

- Response Time
  - Pilots were consistently faster responding to blunder encounters
    - Due to faster initial responses rather than edit times
    - Previous simulation had avg. aircraft response times of **22.75sec** & **10.43sec**
  - Pilots also shown to consistently respond faster to TCAS II Corrective RAs compared to DAA Warning alerts
    - Consistent with instructions/training





Conclusions

❖ Interoperability concept under test shown to support both the basic DAA functionality under nominal conditions (non-blunder encounters) and compliance with DAA and RA guidance

- Losses of DAA well clear & Corrective RAs rare under nominal conditions
  - Pilots proved able to de-conflict from secondary intruders – despite being in close proximity
- Pilots complied with regain DAA well clear and RA guidance at very high rate
  - Less likely to comply with RAs in cases where secondary traffic (undetected by TCAS) would cause an immediate conflict (Use Case 3)
  - Response times to TCAS II RAs within 5sec requirement

❖ Caveat: the design of the study - no secondary tasks or background traffic, high rate of conflicts – likely led to better and more efficient performance than could possible be expected in more representative setting